VOLUME THREE

ENVIRONMENTAL EFFECTS OF NUCLEAR WEAPONS

SUMMARY

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SPECIAL ASPECTS OF ENVIRONMENT RESULTING FROM VARIOUS KINDS OF NUCLEAR WARS

ENVIRONMENTAL EFFECTS OF NUCLEAR WEAPONS

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SUMMARY

ENVIRONMENTAL EFFECTS OF NUCLEAR WAR

1. Weapons Effects Spanning Large Areas

If we divide weapons effects capable of covering large areas into categories based on physical damage mechanisms, there are four major classes:*

radiological:	damage to biological organisms caused by ionizing radiation
thermal:	damage caused by heat or fire
meteorological:	damage caused by changes in weather or climate, triggered by catalytic action of nuclear debris in the atmosphere
secondary:	damage caused by a "domino" effect due to selective removal or modification of a constraint normally contributing to environmental homeostasis. Within this category we have included epidemiological problems affecting humans, livestock and crops; outbreaks of pests (especially insects); changes in ground surface temperature and humidity characteristics (microclimate); secondary fires; local ecological changes; erosion and floods; and "the balance of nature."

2. Radiological Problems

The environmental effects of ionizing radiation will be of primary concern in the event of an attack involving large numbers of groundbursts. An enemy might choose to explode his weapons at or near ground level either to maximize ground shock damage, e.g., against hardened underground targets such as missile sites, or to maximize the extent and intensity of radioactive fallout.

There are three distinct types of damage: (a) whole-body damage, mainly due to penetrating γ-radiation or neutrons, (b) surface burns,

*A fifth category, blast, does not seem to warrant separate discussion, since blast damage is typically much more localized than radiological or thermal damage.

arising from β-radiation, and (c) long-term internal damage due to biological accumulation of certain radioisotopes, particularly Sr-90, Cs-137 and I-131.

Whole-body radiation will be of concern primarily to slowly reproducing, biologically complex (and usually ecologically dominant) species, particularly the larger mammals and trees. Most mammals are apparently about as radiosensitive as man. Birds seem to be a little less sensitive. The most sensitive trees (conifers) seem to be in the same range. Deciduous trees and other plants of importance to man seem to be an order of magnitude more resistant (see Table 1-11). Hence conifer forests are relatively vulnerable to fallout damage. It is important to note that mammals and birds cannot, for the most part, multiply their numbers by large factors in a year.* Thus, if populations are decimated in a particular region, it may take several seasons for repopulation to occur. In the case of forests, effective regeneration is still slower, since it takes a number of years for a tree seedling to grow to maturity.

In addition to the risk of severe sickness or mortality there will be penalties associated with milder doses. Radiation is an "insult" which, in concert with other environmental stresses, may enhance the probability of synergistic (or cooperative) secondary effects such as disease, attack by pests, susceptibility to extreme weather conditions, etc.

Surface damage due to β-radiation will be of primary concern to small organisms, such as insects, and exposed parts of larger organisms, since the β-dose very close to the surface may be as much as 100 times greater than the γ-dosage. Many insect larva or eggs, attached to exposed

*Rodents are exceptional.

surfaces, may be killed by β-radiation, and adult females carrying eggs may be sterilized. Moreover, leaves, buds and young seedlings having direct physical contact with heavy fallout for even a few days are likely to be vulnerable. Established perennial plants, such as trees, can probably tolerate partial defoliation for a season; others such as grasses may die back to ground level and regenerate again from roots. Surface damage may also be important for larger animals. For example, animal species having paws rather than hooves (including carnivora, insectivora and rodenta) may be so badly burned that they are unable to hunt for food. Birds might lose feathers and be unable to fly. Large grazing animals, such as cattle and sheep, might receive serious β-burns on muzzles, tongues, lips and throats, or on external areas of exposed skin (such as scars or brand marks). Such burns could become festering sores which would attract screw-worm flies and other pests.

Internal damage is of primary concern only to man, since other animals would, in general, receive lethal whole-body (or surface) doses long before significant internal concentrations can build up. The isotope Sr-90 is chemically similar to calcium and tends to accumulate in new bone. Whereas the current worry is about "world-wide" fallout, which is absorbed by plants mainly from foliage, the postattack problem is likely to be dominated by uptake from the soil. A chain of arguments discussed in the text suggests that 1 KT/mi^2 (fission products) would lead to a mean lifetime bone marrow β-dose of $\sim$ 70 rem and a maximum lifetime dose of 350 rem. Suitable decontamination measures could, of course, reduce this. The extent of the cancer or leukemia hazard due to doses of this magnitude is very hard to assess quantitatively. However, there is little doubt that if such a hazard is perceived by the public one result would be to force prices of the least contaminated foods higher and to stimulate production of such foods, even if this is agriculturally inefficient.

Cesium-137 is not accumulated in bones, and therefore does not reside as long in the body; moreover, it is a γ-emitter, which means the internal dose is not concentrated on a particularly susceptible region but is distributed uniformly. For these reasons the hazard is thought to be at least an order of magnitude less than Sr-90. The third important isotope is Iodine-131, which is concentrated and retained in the thyroid gland. Again, the extent of the long-term hazard is highly uncertain; however, it may be easier to protect against since the isotope decays fairly rapidly and would not pose serious problems unless ingested within a few months of the attack.

The combined effects (including secondary attacks by pests, etc.) of fallout on forests would almost surely weigh most heavily against the dominant species (trees), resulting in a tendency to revert to a pre-climax stage in which mixed herbaceous annuals predominate. As pointed out already, deciduous trees are much less vulnerable than conifers, however. It must be noted, for instance, that bark beetles, which do most damage to trees, are not likely to be affected much by either γ- or β-radiation at levels which would leave some trees alive. The adults are typically long-lived, which means the species can reproduce itself even in temporary radiation fields intense enough to kill an entire generation of fertilized eggs or larvae. The vulnerable, fast-growing stages of the insect's life cycle are seldom, if ever, exposed to β-radiation at all, being normally shielded by several centimeters of bark.

The combined effects on grasslands or croplands appear likely to be different. The β-activity of a layer of fallout deposited on the soil surface would act as a "barrier" to any organism growing (or migrating) through it. However, established plants, especially those with woody stems, would be relatively unaffected, as would dormant seeds, insects living entirely underground, and roots of perennial grasses, etc. One season's crops or forage might be badly damaged by the radiation, but it is likely that long-term consequences would be negligible.

Table 1-2

Fission Products and Sr-90 Due to 1-MT Surface Burst

Isodose Contour (R/hr at 1 hr)	Soluble Sr-90 per Unit Area (mC/mi^2)	Areas Between Isodose Lines (mi^2)	
	Miller	Miller	ENW
1-3	25-75	2600	4000
3-10	75-250	2400	5500
10-30	250-750	1800	4950
30-100	750-2500	1550	3250
100-300	2500-7500	1000	1000
300-1000	several thousand	870	360
> 1000	several thousand	-	340

Although fission products are not deposited uniformly (Table 1-2) it is convenient for purposes of assessing vulnerabilities of area targets to begin by assuming a uniform effective density D_E of fission products. To allow for non-uniformities of distribution, and various shielding effects, we introduce two "inefficiency" multipliers Q_R and S_R, from which one can estimate the density (KT/mi^2) actually required to produce a given result, i.e., $D = Q_R S_R D_E$. Similar multipliers Q_T, S_T are introduced in the text for thermal effects. Results of a sample calculation are shown in Section 9 of this summary and Chapter VII of the main report.

Table 1-11

Radiosensitivities of Communities

		LD_{50-30} (R)	D_E(crit)* (KT/mi^2)
Vertebrates	Mammals	300-800	--
	Birds	~1000	--
Insects (8 species) (sterilization dose)		1000-6000	--
Conifers (5 species)		750-1000	~.06
Wheat, corn, oats, rye, barley		3000	~.18
Sorghum		~5500	~.33
Deciduous trees (5 species)		~6000-7000	~.45
Potatoes		~9000	~.55
Soybeans		~10,000	~.60

3. Fire Problems

Damage resulting from thermal flash, or fires ignited subsequently in areas containing inflammable materials, would be of primary concern in the event of an attack designed to maximize the radius of destruction by atmospheric blast waves, or to cause thermal damage, e.g. against cities, "soft" military targets, or environmental targets.

Small (KT) weapons will cause ignitions at slightly lower values of energy flux at the target than large (MT) weapons. Moreover, materials vary considerably in their intrinsic ignitability, and a given material is more or less easy to ignite in accordance with water content, which, in turn, depends on ambient humidity. However, it is probably reasonable to assume that a flux of 10 cal/cm^2 delivered by a MT weapon would be sufficient to cause ignitions over large areas with typical mixtures of fuel types.

*Based on accumulated 30-day dose from uniformly distributed fission products, and assuming LD_{90}'s are about 25% higher than LD_{50}.

The range R at which ignition will occur depends very strongly on weather conditions. On a clear day, a 10-MT weapon may start fires at a distance of 18 miles or more, whereas on a moderately cloudly day the range may fall to 6 miles or so, and on a day of heavy cloud it will be negligible. The areas involved vary as the square of the range. Thus, in the first case, a thousand square miles might be affected, whereas in the third case, only a relatively few.

The probability of fires spreading also depends strongly on weather, both at the time and for a number of days preceding. In the winter, the chances of uncheckable fire spread are negligible over most of the forested parts of the country. In peak summer, such conditions might occur 6% of the time, with intermediate probabilities in spring and fall.

Because a fire, once started, has little or no "memory" of how it began (e.g., from one point, many points, or from a "line" source), it is felt that estimates of linear spread, α, along the line of wind direction, can be made on the basis of data derived from peacetime experience with fires occurring under particular kinds of weather conditions. Estimates made on this basis are shown (Table 2-6). Other investigators believe the fractional fire spread would be much higher, however, so the question remains open.

In exceptional circumstances, i.e., when wind velocities are low and fuel density is high, simultaneous ignitions over a large area may result in a stationary pattern of concentrically converging winds, called a "firestorm." Firestorms have taken place in some cities seeded by incendiary bombs (Hamburg, Dresden) and at Hiroshima; a similar localized phenomenon may sometimes occur in forest fires. If large-scale firestorms are created by high-altitude MT bursts, the results could be extremely destructive and subsequent recovery would be impeded because of the lack of surviving refugia from which repopulation and reseeding can spread. However, this possibility is thought to be quite remote by most experts.

Destruction by fire would affect the long-term prospects of different biomes very unequally. Forests subject to underbrush fires are often the better for it; on the other hand, crown fires are very destructive. Apart from loss of timber (some of which might be salvaged), however, the effect on watersheds might be beneficial, e.g., in dry areas where extra runoff is desirable, or extremely costly in regions where erosion or floods might result. On the other hand, substantial areas of grassland have been invaded by woody brush (e.g., mesquite) primarily because of the systematic suppression of fires in the past. In such areas fires would kill the bushes but allow the grass to grow back the following year, thus improving the pasture. The disutility of human casualties, destruction of livestock, structures, standing crops and timber are obvious, but the long-term environmental effects are less so, and depend on details.

Table 2-6

Ignition and Fire Spread Under Alternative Circumstances

Weather Conditions	1 MT R(mi)	1 MT α(mi)	1 MT A(mi^2)	% Spread	10 MT R(mi)	10 MT α(mi)	10 MT A(mi^2)	% Spread
"No Spread"	3	0	28	0	7	0	155	0
"Actionable"	8	0.15	207	2	18	0.15	1030	1
"Critical"	9	1.4	300	17	21	1.4	1515	8.5

4. Meteorological Effects

There are a number of possible catalytic mechanisms, all of them rather speculative, which might conceivably cause short-term changes in the weather. Two possibilities which look important are (1) enhanced convection (due to heating of large masses of air) might lower the ambient temperature and humidity near the ground; and (2) ionization might increase conductivity and alter electrical characteristics of the atmosphere. Since the weather is variable anyhow, there would be little harm or significance in mere rearrangements; for example, rescheduling rain from Monday to Thursday and blue skies from Sunday to Tuesday. However, other possibilities also exist; for example, the storm track might conceivably be shifted north or south; storminess may increase or decrease; temperature maxima and/or minima may become more extreme; total global precipitation may alter.

Longer-term effects are also possible. If a large number of weapons should be exploded near the ground, enough fine "dust" might be injected into the stratosphere, where it would drift down very slowly, to interfere with the solar energy input to the earth by scattering a substantial fraction of it back into space. Such an effect would alter the earth's energy balance and consequently the circulation of the atmosphere. If a sufficiently large war (> 10,000 MT's) should occur, and if the scientific uncertainties should turn out to be on the unfavorable side, it is not even inconceivable that a new ice age might be triggered. More likely, however, would be the less dramatic climatic consequences such as a temporary cold spell with temperatures averaging a few degrees below normal, possibly resulting in reduced yields for some crops and other ecological disturbances. Although this does not sound serious in comparison with other disutilities of the war, it would be an added stress whose consequences might be magnified considerably, occurring in conjunction with widespread radioactivity, economic disruption, and so forth. Some calculations are presented in Appendices B and C.

5. Secondary Damage

Most types of secondary damage, as far as can be envisioned, would be similar in kind to natural disasters of common experience. The question is, to what extent would either the frequency or magnitude of these various types of occurrence change as a result of a nuclear war? Such a change might be brought about because one or more of the natural or artificial constraints, which normally operate to maintain stability (or homeostasis), are modified or removed.

Epidemics. The major constraints against epidemics are:

(i) widespread public awareness and practice of the fundamental principles of sanitation;

(ii) advanced diagnostic techniques permitting early identification of potential threats, which, in turn, makes it possible to mobilize resources where they can be used most effectively;

(iii) artificial barriers such as vaccination, sewage treatment, water sterilization, government monitoring of commercial food processing, deliberate suppression of disease vectors (i.e., mosquitoes, rats, etc.);

(iv) medical countermeasures: hospitals, antibiotics, etc.;

(v) natural physiological resistance.

It is obvious that in the aftermath of nuclear attack all of these constraints (including the last) would be degraded to some extent. On the other hand, in no circumstances would external conditions seem likely to approach those characteristics of great historical epidemics such as the black plague. Even if every hospital and antibiotic were destroyed, the basic habits of sanitation and knowledge of the dynamics of epidemic disease would still exist. Moreover, one legacy of the preattack period would be a residue of acquired immunity (via vaccinations) or absence of major sources of infection. The one major caveat is that we cannot compare the natural physiological resistance of a postattack 20th-century population with any previous one. The combined death rate from infectious diseases could conceivably be an order of magnitude greater than it is today, while almost certainly remaining very much lower than the average for the Middle Ages, and probably lower than for World War I.

Pest Outbreaks. The analysis is somewhat parallel with the epidemic case, except that the emphasis is on constraints on population growth (rather than spread). For insect pests the constraints are very complex, but a succinct statement of the conditions for an outbreak might be something like the following: simultaneous availability of appropriate, protected* site for eggs, adjacent to an appropriate, protected food supply for larvae (the most vulnerable stage). Insect numbers are limited in nature because such fortuitous combinations of circumstances seldom occur in a natural community. Healthy plants, for instance, do not offer such ideal havens because they usually have protective defense mechanisms of their own (such as manufacturing substances like nicotine which are toxic to insects). Such a plant can be overwhelmed by force of numbers, but not without taking a toll. Man's activities merely make life more hazardous for insects than it would already have been.

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*Protected from predators, parasites, extreme temperatures, etc.

However, it has been known for a long time that one-crop farming creates favorable conditions for outbreaks, if once the process of population build-up gets well under way. Anything which weakens the plants seriously (such as drought, fire, freezing weather, or ionizing radiation) will open the door to pests. At this point, usually, only heavy applications of insecticides or some other heroic measure can turn the tide. If man is unable to interfere effectively at this point, the outbreak might soon be uncontrollable. Nuclear war could affect the situation unfavorably, both by adding stresses on the plant communities and by reducing the ability of man to interfere. On the other hand, it is apparently unlikely that aftereffects of nuclear attack would appreciably relieve insects from existing pressures from predation or parasitism except in localized instances.*

Very similar conditions govern the populations of rodents, birds, etc., except that the requirement is for an ample food supply adjacent to adequate shelter. As a rule there is plenty of food in summer but it is more difficult to fulfill the conditions in winter. Aftermath of nuclear attack would almost certainly create favorable havens, e.g., for rats in destroyed or damaged cities, but it is less easy to see how rural rodent populations might much benefit except, perhaps, through selective destruction (or incapacitation) of their principal enemies including man. However, differential vulnerabilities are not great.

In summary, insects seem likely to be a greater threat than rodents, but if farmers reverted to a more diversified 19th-century pattern of cultivation, the expected loss because of insects would seem to be less than that of a century ago. Again, the basic reason is that more is known of

*Most insect predation is due to other arthropods (rather than, e.g., birds).

the habits and vulnerabilities of insects and they can be controlled largely by cultural methods such as crop rotation. Limited resources (e.g., of insecticides) could then be held back and used to good advantage to blunt the most serious incipient outbreaks.

Microclimate. One consequence of extensive deforestation could be a change in the climate near the ground, in the direction of greater extremes of soil temperatures and decreased transpiration (combined with greater surface runoff), resulting in lower humidity. Since this alteration in the environment would favor different natural plant communities--presumably those characteristic of more arid areas--the change might become permanent, at least in parts of the country.* In some areas forests might be succeeded by economically valuable grasslands; in others, (conceivably) by desert vegetation. There is some argument, at present, over whether total rainfall might also decrease. Whether this effect would occur or not is uncertain, but it is fairly clear that the over-all water vapor content of the air (excluding the layer near the ground) would not change appreciably. Historical evidence, such as it is, suggests a modest, but not radical, decrease in precipitation.

Secondary Fires and Ecological Succession. Secondary fires, as distinct from fires ignited by the nuclear weapons themselves, are essentially fires of natural origin. The major difference between the preattack and postattack situation is that, in the latter case, a large area--especially of conifer forests--might be killed by a combination of stresses including radiation, disease and insects.

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*It has been suggested that much of North Africa has become a desert in historical times largely because of deforestation.

It is known that dead forests are far more inflammable than green ones, due mainly to the lack of transpiration and lower humidity, mentioned previously. Conditions of extreme fire hazard may occur after only one or two weeks of dry weather, as compared with four to six weeks for live forests. This increases the probability of such conditions tremendously; whereas extreme fire hazards normally occur on about 3% of the days in the year, where the trees are dead the fraction may be 15% or more (depending on area). The author's estimate, based on various known factors and informed opinions, puts the expected destruction by fire in radiation (or otherwise) killed forests at about* 5 times higher than normal.

The disutility of the damage may not be especially great. The salvage value of the timber probably decreases after burning, though not necessarily to zero. The worst penalty is probably increased erosion due to destruction of the litter covering the soil surface. Soils may be damaged somewhat as a result of heat; on the other hand, the heat may facilitate reseeding in some instances. Specific consequences depend on cases.

Ecological aftereffects may be either beneficial or deleterious, e.g., in terms of the palatability of the vegetation to animals, runoff (available for irrigation), desirability of timber, etc. None of these hypothetical alterations seems likely to be especially important.

Erosion, Floods and Silting. Again, these effects would be qualitatively similar to preattack experience. The question is, would the process of erosion be substantially intensified and, if so, would the risk of floods (and silting) be increased thereby? The answer to the first question is, unquestionably, affirmative since the principal natural constraint to the

*Say 3-7.

erosive forces of weather--water and wind--is vegetation. The rate of erosion increases in direct proportion to the depletion of ground cover, as past experience of overgrazing and plowing on hillsides has amply demonstrated.

At first glance it might appear that the risk of floods would increase simply because the removal of vegetation tends to increase runoff. This argument is not strictly valid, since most of the water deposited by large storms (which are responsible for the worst floods) runs off anyhow, because of the limited capacity of the vegetation and soil to accept and store water. However, more to the point, the rate of runoff is drastically increased if there is no vegetation to slow it down. Hence the water tends to find its way into the streams almost immediately--instead of over a period of hours or days--and the peak flow is correspondingly greater. Thus, upstream floods might (in some cases) increase in destructiveness by orders of magnitude. Silting behind dams would increase correspondingly.

Downstream, the large numbers of tributaries, with peak flows arriving at the main stream "out of phase" with each other, would tend to even things out. In this case a flood would be greater only if the total volume of water were greater. Because of the saturation phenomenon mentioned above, the volume of water from a given storm would not be much different. However, the major floods of big rivers occur in spring when rains combine with runoff from the melting of accumulated winter snows. Melt water may run off on the surface or soak into the ground, depending on whether the frost in the earth is solid (concrete) or permeable. The latter situation is typical of ground in living forests, whereas the soil in an area without vegetation may freeze solid. Thus total spring runoff from snow is likely to be greater after the ground cover is depleted. The percentage increase of downstream flow may not be great (e.g., $\sim$ 10-20%), but if this is superimposed on a maximal flood, the destruction could be unprecedented.* The "expected" downstream damage, on the other hand, would probably be within the normal range.

Balance of Nature. The term "balance of nature" is something of a misnomer--implying a kind of unstable equilibrium**--whereas, in fact, "nature" has withstood and adjusted to very large perturbations in the past. Moreover, many previous disturbances, both sudden and gradual, have exceeded in magnitude (of energy released) most plausible nuclear wars. It is somewhat harder to determine whether past violent disturbances such as earthquakes and storms are comparable to nuclear wars in terms of biological effectiveness or "coupling coefficient"; however, it seems clear that the chemical pollution of the environment by industrial civilization would have comparable or greater biological effectiveness (see Table 4-7).

In summary, neither general arguments based on the "balance" metaphor, nor specific known mechanisms (discussed previously), suggest any reason to believe the balance of nature would be permanently affected by a nuclear attack.

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*Kinetic energy of a flood scales roughly as the 4/3 power of stream flow volume.

**Analogous to a tight-rope walker.

Table 4-7

Magnitudes of Historical Disasters

Event	Date	Estimated Energy in MT's	Uncertainty Factor*
Vredefort meteorite (S. Africa)	prehistoric	2,500,000	>10
Ries Kessel meteorite (Germany)	prehistoric	500,000	>10
Tomboro volcano	1815	112,000	3
Coseguina volcano	1835	44,000	3
Krakatoa volcano	1883	20,000	3
Wei-Ho earthquake	1556	6,500	3
Lisbon earthquake	1775	3,500	3
Chile earthquake	1960	1,500	3
Tunguska meteorite	1908	700	±50%
Forest fire, Paraná, Brazil	1963	360	±50%
Forest fire, Peshtigo, Wisc.	1871	300	±50%
Eastern seaboard hurricane (e.g., "Carla")-instantaneous kinetic energy only**	1961	170	±25%
Arizona meteorite	prehistoric	36	>10

6. Theoretical Approaches

The various problems of prediction posed in the preceding sections differ widely in detail, but suggest some broad common features. In our present stage of incomplete knowledge, a deterministic "analytic" treatment is clearly impractical. Any approach with a hope of success must be

*Most of the numbers are fairly uncertain, but by no means equally so. We have mainly given the geometrical mean of the likely limits. Thus, if the given uncertainty factor is 10, the correct figure is presumably somewhere in the range between 10 times larger and 10 times smaller (i.e., 1/10). For uncertainties less than a factor of 2 it is more convenient to express the range in terms of per cent, hence the given number may be thought of as the arithmetical, rather than the geometrical, mean of the limits.

**Total energy dissipated would be much larger.

statistical in nature, which means populations or communities must be described in terms of distribution functions with respect to relevant characteristics. A natural example of such a distribution would be the relative number of individuals (in a given population) which would succumb to a stated environmental stress, such as ionizing radiation or disease, as a function of either dose or "state-of-health."* Once the characteristics of populations have been so described, one has a quantitative method of predicting the response to a greater stress (or dose) than has been experienced in the past. Moreover, one can begin to approach the vexing problem of predicting the response of such a population to multiple stresses.

Another prototype distribution, which appears again and again in a variety of forms, is the frequency of a particular type of natural event (i.e., a disaster) as a function of the magnitude thereof. Such functions can often be derived (in principle) from simple compilations of historical data, e.g.,

Frequency of (Event)	As a Function of (Measure of Magnitude)
floods	discharge volume
hurricanes	kinetic energy
fires	square miles burned
fire weather conditions (hazard index)	fire spread rate
earthquakes	Richter magnitude or energy released
epidemics	number of cases or number of deaths
pest outbreaks	area covered or total damage
etc.	etc.

Typically, the functional form of such distributions takes a relatively simple mathematical form (which can sometimes be read directly from a plot on log-log paper). Once the form of the frequency vs. magnitude

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*This concept must be made precise to be meaningful, but that is a separate problem.

curve is known, one can calculate the expectation value of such an event, as a function of the parameters of the distribution. The problem of predicting expected value under altered circumstances is reduced to a problem of determining how the parameters scale. Sometimes this can be done with reasonable confidence from purely theoretical considerations,* but even where this is not feasible, one can perhaps design experiments which will begin to yield the right kind of data. Appendices D, E and F discuss some of these approaches in more detail.

7. Disutility

Having described the physical effects (i.e., damage) due to nuclear weapons, both direct and indirect, one must face the fact that disutility is not equivalent to damage, although the two are clearly related. In too many calculations of the "cost-effectiveness" of damage-limiting systems (for example) the criterion of effectiveness is taken as "lives saved" or "dollars saved."

In the first place, disutility is not simply an index of dollars or lives, but somehow contains both plus some mix of other imponderables such as "national prestige," "democratic ideals," "Christian ethics," aesthetic values, etc. The weights that one person will assign to these diverse values will differ from those of another.

Secondly, even if one throws out all the variables which cannot be quantified, coming back to dollars (or lives), it is immediately obvious that disutility is a nonlinear function of the variable(s). The simplest

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*Consider the case of fires: assuming the probability of occurrence of various weather conditions is unchanged, the expected total spread scales linearly with the number of ignitions (or the number of weapons).

demonstration is that if one starts with 100 dollars and loses 25, one is sad; if a second 25 is lost, one still has 50 left--a misfortune but not a disaster. Losing the third 25 is a very serious matter, however, and the loss of the last 25 is a calamity. A loss which leaves something left is much easier to bear than the loss of the whole, especially where recovery depends on having some capital to build upon.

On analyzing the reasons for this, one is led to the conclusion that (1) disutility is a nonlinear function of initial damage, and (2) disutility can be defined for purposes of discussion as the cumulative loss integrated over time until recovery is complete.

The above intuitive definition seems to fit our subjective notions reasonably well. Since the first requirement must also be met, any proposed mathematical model for describing recovery can be tested against this criterion, which turns out to be a non-trivial constraint. See Appendix G.

8. Extreme Cases

One major difficulty in evaluating potential disutilities due to nuclear attack is that upper bounds are so hard to calculate. Many of the mechanisms which can be envisioned, especially those in the "domino effect" category, appear at first glance to be open-ended. That is, there is no apparent reason why fires, epidemics, pest outbreaks, etc., could not sweep the whole country. The analysis we have attempted to give, in most cases, is based not on detailed understanding of the operation of the interactions (generally lacking), but on the past performances of the "system" in comparable, if admittedly not identical, circumstances. It is clear that the confidence level of this type of argument is minimal; yet at present there is little prospect of doing better.

Two types of weapons effects can, however, be estimated with a slightly higher degree of certainty, namely, radiological and thermal hazards. It seems useful to attempt this calculation, despite the unsatisfactory state of the basic data.

The following charts summarize the results for a (roughly) 90% kill criterion. It must be noted that the figures for radiological effects refer to fission KT only, which means they should be multiplied by a factor of 2 if 50% fission weapons are used, etc. The thermal effects are estimated assuming "average clear" weather for the entire country--a very unlikely assumption, but a condition worth considering as an extreme case. Wherever rain or heavy clouds occur, the ignition radii will drop to small fractions of the clear weather values, and areas burned would be smaller accordingly. The parameters Q_R, S_R, Q_T, S_T are inefficiencies (see text).

Table 6-2

Extreme Damage Criteria*

Target Biome	Radiological Effective Density D_E KT/mi^2	Thermal Effective Density D_E KT/mi^2
Cultivated Land	.5	0.25
Grasslands & Pastures	.5	0.25
Confier Forests	.03	0.25
Deciduous Forests	.5	0.25

Table 6-4

Extreme Environmental Attack

		Radiological		Thermal	
Target Biome	Area (mi^2)	$Q_RS_RD_E$	Weight (MT) Fission	$Q_TS_TD_E$	Weight (MT)
Cultivated Land	615,000	~13	~ 8,000	16	~10,000
Grasslands & Pastures	1,050,000	~13	~13,000	8	~ 8,700
Conifer Forests	540,000	~ 1	~ 540	16	~ 9,000
Deciduous Forests	420,000	~50	~21,000	16	~ 7,000

*In comparing the two columns it must be kept in mind that KT in the radiological effects column refers to fission products only.

9. Environmental-Economic Considerations

A central issue for postattack recovery is the problem of agriculture and food supply. The problem may be acute because there is reason to believe that food productivity is likely to survive less readily than population, even without extensive protective measures. This question deserves further study. However, the basic reasons for concern have to do with the fact that modern agriculture is a complex system, based on the availability of inputs from other sectors of the economy such as transportation, petroleum fuel, machinery, commercial seed, insecticides, fertilizers, and animal feeds. This interdependence means that actual production may be substantially below theoretical capacity due to "bottlenecks" arising from selective damage to other industries or transportation links.

The obvious way to adjust to the altered postattack situation is to rely much more heavily on Calories from vegetable sources than preattack. However, this is not an easy solution for two reasons. In the first place, a vegetarian diet is likely to be seriously substandard in several important respects unless vitamin, mineral and possibly protein supplements are available. A substandard diet would substantially reduce the capacity of the population to work, which could, in an extreme case, lead to a self-perpetuating situation from which recovery would be greatly impeded. Moreover, diversion of all Calories from cultivated feed crops to human consumption would force farmers to slaughter many cattle and most hogs and poultry. Cattle, in particular, do not reproduce rapidly so that if beef and dairy herds were decimated it would take many years to build them up again. Farmers would naturally be reluctant to see this happen and might try to withhold feed grains to preserve their livestock. Tendencies in this direction might be magnified by the existence of a Sr-90 contamination problem, which can be ameliorated if food can be obtained from animal sources. Price differentials between animal and vegetable products could be increased considerably by public competition for the one and reluctance to consume the other. This would lead to serious consequences for total Calorie production.

Table 7-5

Comparison of Several Cases

Measure		Counterforce (CF) Attack	Mixed Counterforce (CF) & Countervalue (CV)
Weight:		*	*
population survival	no protection	68%	19%
	"available" protection	88%	38%
livestock survival		41%	27%
cropland available		34%	19%
agricultural production**	no protection	25%	13%
	"available" protection	35%	21%

Table 7-6

Summary Comparison

Attack	Calories/cap. (postattack) / Calories/cap. (preattack)
CF - no protection	12.2%
CF - available protection	13.3%
CF + CV - no protection	22.7%
CF + CV - available protection	18.5%

*The total number of MT's (19,000 and 23,000) is misleading because these attacks were apparently calculated on the basis of much lower value of $\frac{\text{R/hr at 1 hr}}{\text{KT/mi}^2}$ than the "magic number" assumed in Chapter I. These attacks are roughly equivalent to 6-7,000 MT's (fission) in terms of radiological effects.

**Calculated on the basis of the diversion of feed grain to direct human consumption.

10. Countermeasures

A number of measures can be envisioned which might help ameliorate the problem outlined in the previous section.

1. Land classification: A program similar to the soil bank might be put into effect which would allocate the most heavily contaminated acreage for non-food crops, less contaminated areas for animal feeds, etc.

2. Food classification: At the processing plant, batches of food from common sources might be tested and labeled according to Sr-90 level. The least contaminated products might be reserved for babies or children, etc.

3. Food decontamination: Milk can be decontaminated with approximately 90% effectiveness by electrodialysis or ion-exchange methods which would cost roughly 1¢ per quart on a large-scale basis. Liquified foods, juices or beer might also be processed in this manner, although the technology is undeveloped.

4. Land decontamination and protection: There may be some advantage in certain cases in planting deep-rooted crops, or adding lime to contaminated soil. However, the most likely method would be to remove a layer ($\sim$ 2") of top soil (or sod) by means of scrapers or bulldozers. Using modern equipment, this would cost roughly \$40-45 per acre. Polyethylene films may be used to protect soil against fallout if it is spread before an attack. Costs would be roughly \$100 per acre at current prices. However, production would probably have to be stepped up to permit this method to be used extensively. It has a number of advantages which might compensate for higher costs, e.g., weed suppression and water conservation.

5. Stockpiles: The currently available food supply in the United States amounts to something over one year, on the basis of 3,000 Cal./capita.

Agricultural surpluses are shrinking rapidly, however, and may disappear in 3 or 4 years. A diet based on stockpiled grains would be deficient in calcium, vitamin A, vitamin B_2, vitamin B_{12} and vitamin C. The first can be supplied cheaply from mineral sources (limestone). A one-year supply of the other vitamins would cost about $37 million, based on 1963 prices. Other possible stockpile items include frozen sperm from champion bulls, pesticides, fertilizer, gasoline, etc.

6. Imports: Canada appears to be the only reliable source of substantial help after an attack. The rest of the countries of the world are not likely to be able to export large quantities of grain or livestock, even if shipping and port facilities are available (which is questionable).

7. Protection for animals: There may be "do-it-yourself" programs which could be carried out in a crisis situation which would increase PF's of cattle barns, poultry houses, etc., by factors of 3 or 5. It would be important for farmers to decide whether to risk exposure to themselves while feeding and milking during the first few days. A direct reading instrument which records cumulative dose could be particularly valuable.

8. Synthetic sources: Algae and petroleum fermentation have been discussed as possible dietary supplements, but these seem too far from practice to be of importance in a postattack situation. However, brewers' yeast is a valuable food which can be produced industrially on a large scale in equipment normally used for beer production (with minor modifications). Raw materials would be sugar, which could be obtained from cellulose, plus phosphoric acid and ammonia or urea.

GLOSSARY OF SPECIAL TERMS AND ABBREVIATIONS

Synergistic effects:	Effects produced by multiple causes acting in concert.
Homeostasis:	A dynamic equilibrium, brought about by a number of self-correcting mechanisms which tend to counteract any perturbation.
Isodose contour:	A line on a map connecting all points receiving the same net dose of radiation from fallout (analogous to isotherms or isobars on weather maps).
LD_{50-30}:	Dose which would be lethal for 50% of the population in 30 days.
LD_{90}:	Lethal dose for 90% of the population.
D_E:	Effective density (of fission products) in KT/mi^2.
Q_R:	Inefficiency of radiological effects from fallout, due to non-uniform distribution over an area.
S_R:	Inefficiency of radiological effects due to shielding.
Q_T:	Inefficiency of thermal ignition, due to non-uniform deposition.
S_T:	Inefficiency of thermal ignitions due to shielding by the atmosphere (and clouds).